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From Prof. Wood's

No. 10.--University Series.

# MYSTERIES
# OF THE VOICE AND EAR.

BY

PROF. O. N. ROOD,

COLUMBIA COLLEGE, NEW YORK.

*NEW HAVEN, CONN.:*
CHARLES C. CHATFIELD & CO.
1873.

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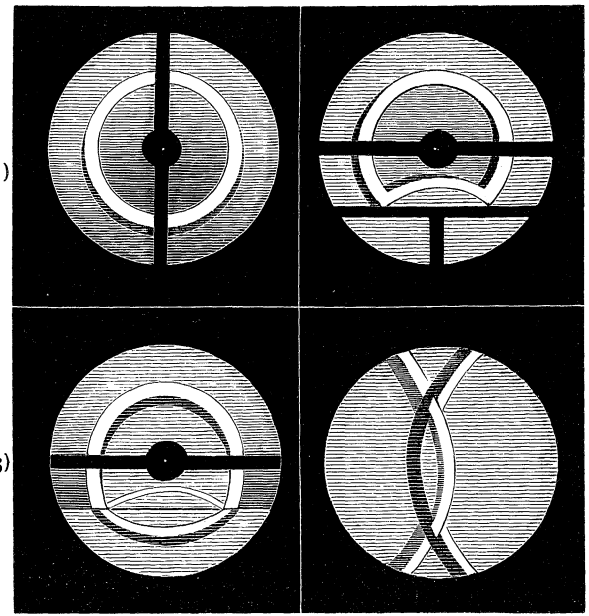

Sound Wave. (1)

Reflexion of a Sound Wave. (2)

Refraction of Sound Waves. (3)

Interference of two Sound Waves. (4)

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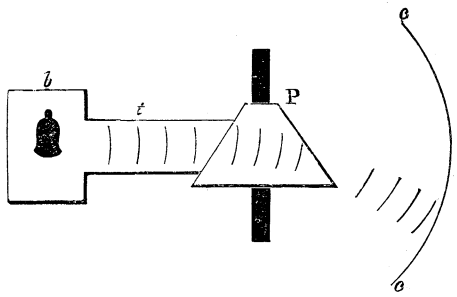


Fig. I.—About Refraction of Sound.

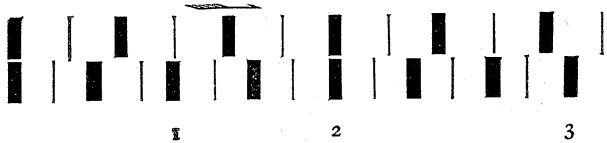


Fig. III.—About the Interference of Two Sound Waves.

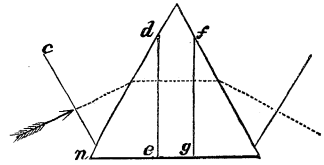


Fig. II —About Soldiers and Ploughed Field.

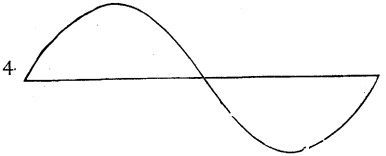


Fig. IV.—About the Combination of Waves of diff. lengths.

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# Mysteries of the Voice and Ear.

Probably every person who is present to-night has at some time stood on a sea beach, and watched the long lines of advancing waves as they swept inward, only to be followed by others, in a perpetual, monotonous succession, so that it seemed as though the ocean was actually sending towards the coast vast masses of water from its inexhaustible magazines. But this beautiful appearance, like so much else in our world, is partly illusory; the water is not transported towards the coast, and if the tide happens to be ebbing, it may have a real, though slow, motion away from it. The waves are produced merely by a momentary heaping up of the drops of water, along a great line parallel to the shore—an instant afterwards the drops fall to their old level, and you say the wave has passed that spot.

Can, then, a mere up and down motion produce the appearance of an advancing wave? Yes, if that motion be executed in suitable time, as I will show in an instant; but let me first add, that the motion we are considering can also be reversed—the wave, after it has struck on a precipitous rock, is driven back from the shore, travels outward to the regions that gave it birth, its drops of water meanwhile remaining near their original positions, moving for the most part only upward and downward. (1.)

When this reversal of the wave's motion occurs, we say

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that the wave of water has been reflected, just as the infinitely smaller waves we call light are reflected from a mirror.

Now this transmission and reflection of a wave I can easily show you, under circumstances which forbid the idea of any motion of transportation. I have here a very elastic cord or rope, made of brass wire, wound in a long, thin spiral, and when I strike it with my hand vertically, you see the wave which runs along its whole length, and then, meeting an obstacle in the hand of my assistant, who holds the other end of it, is reflected, returns to me, is again reflected, and so on, a number of times. But the particles of brass in this experiment are moved neither forward nor backward, they simply rise and fall. (2.)

Perhaps this idea may be made still more evident with a little apparatus I devised years ago. It consists of two pieces of window glass painted on one side with black varnish; from one of the glasses some of the varnish has been removed in vertical lines, while on the other a wave line has been traced by the same means. Placing one of these glass slides over the other, and then holding the combination in the magic lantern, it constitutes a convenient apparatus for exhibiting the nature of wave movement to a large audience, and as you see, we now have on the screen a row of small bright spots, intended to represent a line of material particles at rest. I can communicate to them a wave-like motion by moving one of the slides, so that we now have distinct waves advancing along their whole length, and although these waves are so plain, pray notice that each particle merely rises and falls, in suitable time. Hence to sum up: in the case of a wave of water, it is the

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motion which advances, not the material, and this advance of the motion may be brought about as we have seen, by a movement of the material particles at right angles to the direction of the advancing wave.

Strangely enough there is another kind of motion, which can be communicated to a row of material particles, which also will generate along them, waves, but waves of a different character. In these new waves, which will give us so much occupation to-night, the particles are not pushed aside out of line, as in waves of water or light, but at one instant are crowded together, and afterwards fly apart, remaining, however, always in the same original line. I have contrived a little piece of apparatus which will make the nature of this singular action evident. We have upon the screen a row of spots of light, representing material particles, and you readily see how this alternate condensation and expansion affects them, and it is plain that they are transmitting a series of wave-like impulses. If you select any individual particle for observation, you easily notice, that at one instant it presses nearer its neighbors, and the next retreats from them, each particle beginning and ending this swaying motion in such time that the general effect is that of a wave in motion. I gave an experimental illustration of the first-class of waves with the brass cord, and will now add, that its spirals will just as easily transmit the waves we are now considering, though of course you could not see them. If you should hold the end of the cord, you would, however, be able to feel them, for when they struck your hand they would give it a little push and a pull. This thin elastic box will answer our purpose. I attach the end of the cord to it, and send along it one of these waves; as it

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strikes the box a sharp distinct sound is produced, in fact a series, owing to repeated reflections of the wave, which I generated merely bo pulling back with my finger nail for an instant, one of the spirals.

The air with which we are surrounded is capable of transmitting such waves as these, and when they strike upon our ears we say we hear a sound. I cannot at all to-night even indicate the experiments and reasoning which many years ago forced physicists to believe in the existence of these sound-waves, which they had never seen and never hoped to see ; but perhaps we may do better than thus to consume our time. Let us ask ourselves, what ought to be the appearance of one of these sound-waves out in the free air, and we will suppose, for simplicity, that it is produced by a single impulse. You know that when a stone is thrown into a quiet pool of water, the wave which is generated is circular ; it expands itself over more and more surface, but always retains the form of a circle ; and analogy tells us that our sound-wave ought also to expand in a circle ; that this circle should exist not only horizontally but upward, downward, in all directions, or that our wave ought to be bounded by a great many such circles. Now, bodies which are thus bounded we call spheres ; the sound-wave ought then, to be round like a globe, and we must think of it as a kind of hollow bubble, which is swiftly growing larger. So much, theory would indicate.

Wonderful as it may seem, the recent advances of science have actually placed in our hands the means of rendering visible these waves of sound, and although it would be quite out of place for me on this occasion to enter into a detailed account of the method by which

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this magical triumph was achieved, still you may be interested in a few hints with regard to the general line of thought followed by Prof. Toepler, to whom we owe these beautiful observations. (3).

A sound-wave consists, as we have seen of a layer of air which is more, and of another which is less compressed than the surrounding atmosphere—in fact, of a layer of denser and rarer air. Now, when light which is traveling through the atmosphere meets with a denser or a rarer layer, it is usually turned a little out of its straight path—a very little, but enough sometimes to render the layer actually visible, if proper optical means are employed. Let me give a rough experimental illustration of this: All the lenses of the magic lantern have been removed, and the screen is illuminated by rays of light which emanate from the ignited lime—that is, which come from one point. The jar in my hand contains a few drops of sulphuric ether, and the upper part of it is filled with its vapor, which, as you know, looks just like the air—that is, it is invisible—is, in fact, a kind of air itself, but denser than our atmosphere. When the jar is uncorked I can pour out this dense air, and you notice on the screen how the divergent beams of light render it visible: we see it streaming out, floating away, and can follow the wavy fluctuations it is subjected to by currents of air. If I had used the hot, rarer air which streams up from a candle flame, it would have been equally visible at a distance of many inches above the flame itself.

In our experiment we plainly saw the layers, which were denser than the atmosphere, by the aid of the deviation of the light which they caused, and it is very evident that if we could only isolate just the particular

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rays concerned, getting thus rid of the overpowering glare of the unaffected light, the whole phenomenon would have been far more distinct. Toepler contrived to do this very thing by the aid of a peculiar screen, and thus was able to deal with the far more subtle variations in density, involved in the case of a sound-wave.

But a steady light, like the one we have employed, would have been of no use in such an experiment; the sound wave travels as fast as a cannon ball, and a light of this character would render visible neither one nor the other. It should be illuminated by an instantaneous flash of light, so that the wave would not have a chance to move perceptibly while lighted up, and for this purpose the electric spark was just what was wanted. Let me make an experiment to illustrate this point: We have before us a disc six feet in diameter, which is being turned so rapidly that you cannot see the design painted on it; the disc looks merely gray. The gas-lights having been turned down, I illuminate our swiftly-spinning disc, from time to time, with the electric spark; it seems to stand still, and you readily see that it actually is painted in great black and white sectors. This talented young German physicist used then the electric spark to illuminate his sound-waves, and the snap of a second electric spark to generate them.

We have now upon the screen the greatly enlarged representation of one of these waves as seen by Toepler's method; it is spherical, as we expected, and beautifully shaded. (See frontispiece, Fig. 1).

But though the sound-waves move so rapidly it is not very difficult to measure their velocity, if they are allowed to run over the distance of a few miles. As is well known, this was accomplished in 1822 by some

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members of the French Academy, using for signals the discharge of cannon in the night time, the difference of time between seeing the flash and hearing the report furnishing the desired information. Among the observers were Humboldt, Gay Lussac and Arago, though it is, perhaps, a little remarkable that to this important experiment, only two nights were devoted. (4). Besides this we have the more careful determinations made by the Dutch shortly afterwards, (5), and finally the exprirments of Bravais and Martins, (6), who measured the velocity of sound in a slanting direction, from the Lake of Brienz upward to a station on the Faulhorn.

These last two observers proved that it travels with the same velocity in an upward direction as on a level, just as is required by the celebrated formula of Laplace. The result of these experiments is, that sound travels through our atmosphere at the rate of about 1,090 ft. per second, if the thermometer stands at 0° Centigrade, or at the freezing point of water; and that its velocity is quickened about 2 feet per second for each additional degree of heat. Recently several pieces of apparatus have been devised by which the velocity of sound can be measured, where the distance traveled over is only a very few feet, so that it is now possible to make this measurement in a very small room.

Suppose that we generate a sharp, short sound, at the open extremity of a tube, the other end being closed by a membrane; the sound impulse reaching the closed end of the tube would announce its arrival by giving the membrane a little push outward, and if we had fastened to it a pencil, this would be caused to make a mark on a sheet of paper at the same instant. Let us now imagine that we had, side by side, *two* such tubes, the second one

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being longer than the first, but bent so that both still terminated side by side, each with its membrane and pencil, and that finally our sheet of paper instead of being stationary, were in motion. Then, under these circumstances, the sound-wave traveling through the shorter tube would make its mark first, and the paper would have a chance to move a few inches before receiving the pencil mark due to the companion wave, and if we knew the rate of the paper's motion, it is evident that we could easily calculate the velocity with which the sound had traveled through the longer tube. This explanation will give an idea of the general principle of a number of new contrivances, with some of which it is even possible to experiment at various temperatures, and on other gases than our atmosphere. A simple and cheap apparatus of this kind was, in 1866, devised by Dr. Ernst Neumann, (7), a school-teacher in Dresden; the difference in the paths of the sound-waves was about twenty feet, although the length of the apparatus was only three; the sound itself was generated by the discharge of a child's brass cannon. The paper was attached to a circular disc arranged like a common grindstone, with a handle which enabled the observer to rotate it. The disc was moved with a velocity of only one turn per second, which was rudely accomplished by watching a seconds pendulum, consisting merely of a ball or weight attached to a string and having a length such as to cause it to vibrate seconds. The mean of a number of observations gave a result far more accurate than could have been expected. I mention this apparatus partly because it illustrates so well the idea I wish to convey, and partly because of its simplicity and cheapness, which offer no obstacles to its introduction into

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every country school, where any attempt is made to give instruction in physicis. Of course by causing the disc to revolve by clock work, it would be possible to greatly reduce the size of the apparatus, while at the same time increasing its accuracy.

Using the same general idea, but causing the sound-waves to act on little gas burners connected with the two membranes, in the same year Ivan Zoch (8) in Erlangen, contrived a far more delicate apparatus, with which he obtained results rivaling those of the French Academy in 1822, although in his case the difference in the paths was only three or four feet. With it he measured the velocity in various gases, and by driving a current of air through during the experiment, was actually able to ascertain the change due to this cause.

A somewhat similar idea was used in the same year by Prof. Quincke,(9) of Berlin in a very beautiful contrivance, where unlike the two preceding, the signal was given not to the eye but to the ear; the two sounds were made to destroy each other, producing silence, in a way which I shall presently explain experimentally. With this apparatus, Dr. Seebeck(10) has proved that in small tubes sound travels slower than in the open air, partly as it would seem owing to friction, and partly to loss of the heat developed by the sound wave itself, through conduction by the walls of the tube. He has also shown that in small tubes the velocity is less in the case of deep notes, than with those that are higher.

May I trespass on your patience to mention one more extraordinary set of measurements of sound-velocity, which recently were obtained by a scholar(11) of Professor Magnus in Berlin, who by indirect methods which I cannot now indicate, actually measured the

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swiftness with which tne sound waves traverse as unlikely substances as stearine, parafine, wax and tallow! finding for example, that the velocity in wax was almost three times as great as in our atmosphere, the result differing but little from that previously obtained by Stefan, another German scientist.

Waves of light, we know can be reflected, and Toepler with his delicate apparatus was actually able to watch the *sound waves* in the act of reflexion; my copy of his drawing is now on the screen, and you notice that the reflected portion is spherical like the original wave. (See frontispiece 2.)

In still another matter the sound waves are found to obey the same law with the waves of light or heat. When I place this triangular glass prisms in the path of the rays of light issuing from the lantern, you notice that they are bent out of their original direction and now fall near the edge of the screen, an experiment so simple that a child could easily repeat it. Not so with the sound waves; owing to their greater length it is far more difficult to experiment on their refraction by a prism, though recently this has been successfully accomplished by an Italian physicist (12). Prof. C. Hajech generated sound waves in the interior of a box b by the aid af a bell which was struck by clock work; traveling along the tube t they reached the prism p, and were refracted by it as indicated in fig. 1. The amount by which they were bent out of their path was ascertained by moving the ear over the graduated circle c c which was in an adjoining room, till the position of maximum intensity had been ascertained. The sides of the prism were made of thin membrane, or paper, or finally of

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sheets of mica. Experiments were performed on hydrogen, ammonia, illuminating gas, carbonic acid and on sulphurous acid gas. Besides these gases two liquids were also employed, ordinary drinking water and water which was saturated with common salt. Amongst other results it was found that the same prism refracted waves of different lengths, (or different tones,) alike. This is not the case with waves of light, for as you must have noticed in the experiment made a moment ago the blue rays were bent more than the red. Hajech farthermore by his measurements ascertained, that the sound refraction, in each case, took place in harmony with the well known velocities of sound in the different gases. Let me explain this; going back to first principles let us ask ourselves the question, why in general should waves of light or sound be refracted by a prism at all? Taking the most familiar illustration, we will suppose the line C N, fig. 2, represents a column of soldiers marching over hard ground in the direction indicated by the arrow and that they reach in a slanting manner a triangular ploughed field. It is evident that the soldier at N will be the first to reach the softer ground, and as he and his companions successively enter it, owing to its yielding nature their progress will be retarded, so that the men at C will all the while gain upon them, and by the time the whole column has entered the field, it will have been turned around somewhat and will occupy the position D E; while in the the ploughed field the column will advance parallel to itself; but on leaving it the soldier at F will now be the first to set foot on hard soil, so that he and his nearest companions will gain on those at G, and finally when the whole column is once more on hard ground, it will

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be found that it has been turned still farther around as indicated in the diagram. Substitute for the column an advancing wave of light or sound, and you have the explanation of their refraction by a retarding medium. To make the matter complete it is only necessary to remember that the forward motion of light or sound is always squarely in front of, or at right angles to the direction of the wave itself, a point which all of you have seen exemplified with the waves of water on a sea beach.

From this explanation it is very evident that the extent to which a wave of sound is refracted by a prism of glass depends on the retardation experienced in the prism, and knowing the velocity of the wave in the air and in the prism, and the angle of the latter, we ought to be able to predict the amount of its retardations and consequently refraction. As I have said, Hajech found that the calculated and observed results agreed remarkably well.

Toepler in his beautiful observations, also, after many attempts, was able actually to see the passage of a sound wave leaving the air and entering carbonic acid gas, and you notice the evident retardation which the wave is experiencing. (See frontispiece 3.)

I wish now to say a few words in regard to the inflexion of waves, or their ability to travel around corners. Waves of water as you all know, quite readily sweep around isolated rocks, the rocks unless quite large affording but little protection from their fury, casting let us say but little shadow, while in your ordinary experience you have noticed that waves of light do not seem to have any such tendency, a circumstance indeed which

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was urged by Newton against the undulatory theory of light. But the waves of light are very minute, and to make a fair comparison we should also let them strike on small obstacles; when this is done, it is found that they readily sweep around them, and reuniting aftewards pursue their path unimpeded. But in the case of our sound waves all obstacles which we can conveniently employ are relatively speaking small, so that these waves experience not the least difficulty in passing around them, the obstacle itself casting almost no acoustic shadow, unless it has large dimensions.

Thus far we have occupied ourselves with single sets of waves, and have supposed the particles of air to be acted on by only one wave at a time—it will however more commonly happen that it is necessary to deal with particles which are at the same instant being acted upon by more than a single wave. Let us take the simplest case and suppose our particles acted on by two equal and similar sound waves: now it may happen under these circumstances that the two waves agree in their action, any particular layer of air being at the same moment subjected to a condensation or rarefaction from both these sources; when this happens the motion of its particles will be twice as great and we shall hear a louder sound. But something else is equally likely to occur: it may happen that just at the moment when the layer ought to be condensed by one wave, its companion attempts to rarify or expand it; these two motions will then neutralize each other, and instead of sound we shall have silence—a case where two sounds generate silence! I can illustrate this with these two similar organ-pipes which give exactly the same note; sound-

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ing them both together gives us a louder tone than either would furnish alone, and now after one or two attempts we have them both in action but furnishing only a faint sound; the silence is not quite perfect, but removing my finger from either of the keys you notice how much louder the tone becomes when we have only one set of waves. We can combine both these experiments into a single one, which though so well known always remains beautiful. I slightly alter the length of the waves furnished by one of the pipes: if now I start both sets of waves fairly together, the condensations and rarefactions being in harmony, this state of things cannot long remain, owing to the inequality in their length, as is shown in Fig. 3, where condensation is marked heavily, rarefaction lightly; already at 1 the condensation coincides with the rarefaction, farther on at 2, the old state of things has again returned, and the condition at 3 is the same with that at 1. Hence in our experiment we must expect to have alternations of sound and silence, the tone rising and swelling to a maximum, then dying away again to repeat itself, &c., and you notice how by slightly varying the length of the waves, I can cause this "beating," as it is called, to take place slowly or rapidly. When it happens slowly, we know that the waves are almost of the same length or the tones almost identical, while a greater difference in the notes instantly calls forth more rapid beats. These beats furnish even to the unmusical ear a most admirable and accurate means of judging of the identity of musical tones, and we shall have occasion to employ them later in some of the demonstrations I wish to make. Let me here introduce an experiment spoken of a few moments ago and which is calculated to de-

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monstrate the *reflexion* of sound by the aid of interferences. Holding at arm's length this Ut3 tuning fork, I direct it towards the wall in front of me, and advancing cautiously soon find a position where the waves of sound reflected from the wall interfere with those which come to me directly from the fork, producing for my ear silence; going a step nearer the sound becomes louder, then fainter, etc., and I have found it possible to render these changes of intensity evident to six or eight persons at a time, they being arranged in line perpendicular to the wall and directly behind each other, their individual distances from the wall determining whether at any moment sound or silence was perceived.

Having advanced thus far, let us draw some comparisons between some of these matters common to light and sound. In the first place then, although sound travels so much more slowly than light, yet the extreme ease with which its velocity can be directly measured is not a little remarkable; the *direct* determination of the velocity of light on the other hand is one of the most difficult of physical problems, and its recent solution by Fizeau and Foucault, one of the most splendid triumphs of physical science. Again, to measure *directly* the refraction of sound is a troublesome work, and the results thus far gained, hardly equal in accuracy those which an intelligent child could easily obtain with a glass prism and a beam of sun light; the same may be said of the reflexion of sound, its study is laborious and difficult, and I think our intelligent boy with his bit of looking glass and beam of sunlight, would in a few minutes outstrip in results the work painfully accomplished by many eminent philosophers with the waves of sound. Then

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the inflexion of sound waves is something we cannot escape from, they are perpetually traveling around corners, but to make corresponding experiments on light requires some knowledge and experience, and there can be no doubt but that the very nature of our civilization has been remarkably influenced by this difference. Suppose that it were always possible to see a human being from any position in which you could hear his voice! And lastly in the matter of interference alone, perhaps light and sound stand more nearly on the same level. It is tolerably easy to observe this property with both kinds of waves.

Let us pass to another point. Waves of water as you well know, differ much in length, the great ocean waves stretching themselves out a hundred feet and more, while the tiny wavelets in quiet water often measure less than an inch. So it is with sound. The deepest tones of the organ, which are almost felt rather than heard, are produced by waves many feet in length, while the shrill sounds emitted by a child's whistle are due to waves only an inch or two long. The pitch of the note depends on the length of the wave; low notes are given by long waves, high notes by those which are short. I have here a couple of flute organ pipes, which are so contrived as to furnish ærial waves of about twice their own length; this two-foot pipe is now sending through the house waves that are about four feet long, and when we compare them with the waves furnished by the shorter pipe, we notice that the latter note is just an octave higher than the first.

As we lengthen the waves, then, the pitch of the note sinks; when they do not attain a length greater than

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about 28 feet, they can still produce the sensation due to musical sounds, but with a greater length the separate waves begin to be perceived as such and the height of the tone can no longer be estimated by the ear, and finally with waves about 70 feet, long the sensation of sound altogether ceases. In the other direction we have also a limit, and when the waves are as short as three or four tenths of an inch, they also cease to affect the nerves of hearing.

The long and short waves travel, however, with the same velocity, and when I sound the two pipes together both notes reach your ears at the same instant, and this would happen if you were a hundred times more distant from me. But in order to do this the short wave must take twice as many steps as its longer companion; it must in the same period of time excute twice as many vibrations; hence, finally, when long waves strike on the drum of the ear they cause it to vibrate slowly, while shorter waves compel it to vibrate more rapidly.

This leads us to the remarkabe conclusion, that if, by any means, we cause the drum of the ear to bend inward and outward, or to vibrate slowly, we shall perceive a *low* note, while, if the process be carried on rapidly, the sensation will be that of one which is *high*. I have here a brass wheel, originally contrived by the celebrated Savart, with its rim cut into teeth, and I can cause them to strike, one after the other, on this visiting card; when this is done slowly, the separate taps are distinctly audible over the whole house, but as I quicken the rate, the taps follow so swiftly that the ear fails to recognize them individually, and we have in their place a musical note—not quite pure—which, as you notice, rises and falls as I change the rate of the wheel's ro-

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tation. If this alteration in rate is effected rapidly, the sounds may be made, as you hear, to resemble human cries, not unlike those of infantile distress or anger. These sounds are sufficiently ludicrous, I admit, but they have for us an important lesson; they teach us that in this purely mechanical way, out of the taps on a card, it is possible to build up sounds which have some resemblance to those uttered by human beings!

I wish, in the next place, to make an analagous experiment, in which the resemblance to musical notes will be more complete. The little piece of apparatus I have in my hand is so contrived that, when set in operation, it allows the air to pass through it in puffs, like those of a tiny locomotive. With the organ bellows I drive a current of air through it, and now, leaning over it, I hear a succession of these puffs, which, as the current of air is increased, will follow each other more rapidly, and also gain in strength. We have at last a deep musical note issuing from it, which, as you notice, rises regularly in pitch each instant, becoming at last quite shrill and loud. The instrument was contrived by Cagniard de la Tour, and is called a syren, because it is capable of uttering its musical tones under water. It is provided with an attachment by which I could easily count the number of puffs emitted in a second, and thus determine the number of impulses due to a given note, and hence, knowing as we do the velocity of sound in the air, easily measure the length of the wave producing that note.

The circumstance that musical notes can be reproduced by a series of taps or other short quick sounds, has led to the construction of an apparatus which is something like an electric telegraph for sound. The

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sound waves issuing from an organ pipe or the human voice, are made to act on a membrane, which by its vibration breaks and re-establishes an electric current, and this latter acting on a rod of iron at a distance of say 300 feet, calls forth from it a corresponding series of taps, and hence reproduces at this distance to some extent the same musical sounds. This is the "Telephon" of Reis, which although still far from perfect, has at least been so much improved recently that it can be used by others besides its inventor, though I do not think that we can hope ever to see it transformed into a true telegraph of sound. (13)

But we must pass on to the consideration of another matter, and will return once more for an illustration to our waves of water. While out at sea, those of you who were able, must have noticed that the large waves of water, which lifted and rolled the ship, were for the most part not simple in form, but covered with minor wavelets which carved their surfaces into ragged and ever changing outlines. They demonstrate for us the possibility of the coexistence of two or more sets of waves, and show us the manifold forms assumed by water acted upon by several independent wave-like impulses. I have in my hand a large tuning-fork which is vibrating in a certain way, and by drawing the fork over this smoked glass, the little wire attached to it renders these vibrations visible, and we have them now delineated on the screen under the form of a straight band, which consists of a multitude of minute waves. But I can also communicate to the fork a second motion, still preserving the first, and you see it has traced on the screen a series of larger waves, whose mountains and valleys are built up of the little undulations. Just so it

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is with the waves of sound; they are often, indeed almost always, thus broken up, it being seldom that simple sounds produced by smooth, clean cut waves reach the ear. Let me give some experimental examples: I sound this mounted tuning fork; it furnishes us with a pure note, and you can observe its quality. This (flute) organ-pipe gives the same note a little mixed with the higher octave, but this reed organ-pipe, which also gives the same fundamental note with the other two, has an entirely different sound, and one might imagine its note was an octave higher than those of its companions; but the notes are the same as is announced by these beats, which I produce by sounding any two of the instruments together, and then lowering the note, of one of them slightly, by holding my hand near the top of the pipe.

The reason of the difference in the case of the reed-pipe is simple; it generates not only the four-foot waves of its companion, but many other sets which are shorter, waves which give the octave, the next higher duodecime, &c. The fundamental or lowest note of the pipe, being mingled with all these noisy companions, fails of course to produce as decided an impression on the ear as otherwise would be the case. Now these reed pipes, with their train of multitudinous notes, have for us, as speaking human beings, a particular interest, and we must pause for a minute to examine their construction. They consist of a vibrating tongue down at the base, which lets the current of air from the bellows pass through in puffs, and generates a set of tones, after the manner of the syren, except that the tongue remaining of the same length, the set of tones is always the same; whereas the tones of the syren, in my experiment, were always changing.

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But can each of these æriel pulses generated by the vibrating tongue really contain a series of waves having different lengths? How is it possible that they all can coexist at the same moment, since the particles of the air certainly cannot actually move at the same instant in two different directions. The experiment with the tuning fork and the smoked glass demonstrates practically the possibility of coexistent motions in a very simple case; there the lengths of the two waves and their heights differed so greatly that you all easily recognized both in the compound curve, which looked like a single wave drawn with a trembling hand. But cases may happen where the resulting curve while it contains two waves of this character, at the same time conceals them. The curves now on the screen are quite definite in character and are known as sine curves; (figures 4 and 5;) figure 6, (the unbroken line,) is produced by combining figures 4 and 5 together; in it we fail to recognize the smaller curve, though it is virtually present and inevitably makes its appearance when we attempt to analyze fig. 6 into two sine curves. The dotted line is the same with figure 4, and shows the degree of variation produced. We might by a process of construction, easily add to fig. 6 a third, a fourth, indeed any number of constituents, each a new sine curve, our resulting curve always assuming a new shape, and a patient analysis of it would finally reveal the presence of all these additions. By the selection of suitable and numerous sine curves even forms can be produced where the likeness to the original shape is quite obliterated and the curvature replaced by straight angular lines. Hence if we should see a wave having a form similar to figure 6, (unbroken line,)

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we should be justified in saying that it virtually contained the waves in fig. 4 and 5, and that our angular wave also virtually contained a very much larger number of constituents of the same general character. All this applies directly to the first class of waves with which we were occupied to-night, but it is no less true of waves of sound. Here we have also a typical form of wave for our point of departure, where each particle swings backwards and forwards obeying the mathematical law which regulates the swings of a pendulum, and this typical motion we can modify at will by causing the particles to be simultaneously acted on by a second, a third, or any number of other waves having different lengths, and as we shall hereafter see, the unaided ear instantly analyzes the complicated resultant wave into its simple constituents.

It is then by the discontinuous action of the vibrating tongue in the reed pipe tnat complex waves are produced, consisting virtually of several sets which vary greatly in length, and they are afterwards strengthened or weakened by the pipe; by altering the shape and size of the pipe you can strengthen or weaken particular notes which are present, and thus give the sound a different quality, without necessarily altering the pitch of the proper or fundamental note. I have here three reed-pipes which give exactly the same fundamental note, but the quality, as you notice, is quite different—one of them giving trumpet-like tones, while the others resemble in sound the hautboy and clarionet.

It was remarked that reed-pipes have an interest for us, and it is because the human vocal apparatus is essen-

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tially built on the plan of a reed-pipe; the membrane in the throat called the "vocal cords," corresponds to the vibrating tongue, and the cavity of the mouth and nose has the same functions as the pipe. The section of a head on the screen shows the relation of these parts.

Let us make some comparative experiments: I have here the vibrating tongue or reed, without its pipe, and driving the air ot the bellows through it, can, by varying the acting size of the tongue, draw from it a series of different notes, which have a quality that is evidently due to complexity; none of the notes sound in the least like that of the tuning fork. Corresponding to this I have in my hand artifical human vocal cords made of sheet india-rubber, and as you hear, can by stretching them more or less, draw from them a series of inharmonious semi-human tones, which break up from time to time into an inarticulate howling. I add to my reed a short conical pipe; the quality of its sound is entirely changed, although the fundamental note is unaltered; and opening and closing it with the hand, I easily cause it to pronounce the words, "Ma, Ma." Next I supply my artifical vocal cords with a short broad pipe or cylinder (slightly conical), and they easily utter sounds like "Pop-par." Removing the cylinder and substituting for it this glass flask, we have it pronouncing the words "Pa, Pa," with a somewhat nasal twang.

All this shows that by varying the shape and size of the pipe, or the cavity and opening of the mouth, without in the least altering the fundamental note, we can strengthen or weaken particular sets of the higher notes which accompany it, and thus entirely alter the qualiiy of the resulting sound.

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Many years ago, Willis, in England, found that by mingling certain tones produced by reed-pipes, the vowel sounds could, to some extent, be imitated, but more recently the subject has been examined with great care by Helmholtz, (14), Germany's greatest living physicist.

Let me attempt to convey an idea of the mode in which Helmholtz's analysis of the vowel sounds was performed. You all know that light can be analyzed with a prism of glass and separated into its constituent colors, red, orange, yellow, green, blue and violet. Now, though sound can be refracted by a prisim of gas just like light, it is not possible in this way to analyze a mixed sound into its components; here the prism fails us. But there is another method of analyzing a beam of light and ascertaining its composition: we have now upon the screen a beam of purple light; I hold in my hand a piece of stained glass which will transmit only rays of red light. Let me try to send the purple light through the plate; if *red* rays are present they will easily traverse it, and we shall see them on the screen. Making the experiment then, you see evidently that our purple beam contains red light. Let me now test it with a glass which transmits only green rays, and the result is darkness; evidently green rays are absent; and, now, finally, trying this blue ammonical solution of copper, which stops all rays but the blue and violet, we find that *they* traverse it with ease, and hence conclude that our purple light contains red, blue and violet rays. Now Helmholtz contrived for musical notes pieces of apparatus, which correspond to our plates of stained glass, but vastly surpass them in accuracy of action. These most important instruments he called reasonators; they consist of hollow spheres or cylinders having a definite

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capacity, and provided each with a mouth or opening of a certain size, and any one of them has the remarkable property when applied to the ear, of rendering the experimenter comparatively deaf to all notes but one, and of greatly strengthening that particular note so that attention is instantly called to it when sounded. I I have often amused myself by observing the recurrence of some particular and unconspicuous note during the performance of a complicated piece of music, indicating by a gesture its presence to the musicians, and I can easily show you that one of these resonators actually strengthens the note to which it is attuned, while paying but little attention to other tones. This tuning fork is in vibration, and the sound is too feeble to be heard beyond a very few feet, but when I bring it near the open side of the resonator, the sound is rendered audible over the whole house; trying forks which give other notes you notice that no such strengthening is produced.

The analysis of the tones of the human voice offers greater difficulty, than other sounds of corresponding complexity, from the circumstance, that from chilhood up we all have been accustomed to regard its tones, each as an independent whole, making no attempt to ascertain the musical components employed in any particular case, and hence for its tones the use of resonators became all important. With the aid of these instruments, Helmholtz proved that the vowel sounds are produced by the presence of a fundamental note, mingled with higher harmonicals in various proportions. He even ascertained that the intensity of the *highest* tones varies somewhat in different individuals, being greater in voices that are shrill, than in those whose sound is softer.

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Having gone through this labor the same physicist undertook the artificial reconstruction of the vowel sounds. To accomplish this in a scientific manner it was of course necessary to employ pure tones, and these are most easily obtained by the use of tuning forks. One of these instruments, alone by itself, furnishes, as you notice, a sound which at a little distance is quite inaudible, but by causing it to vibrate directly in front of a hollow metalic cylinder of exactly the right capacity, its sound is greatly strengthened, and can now be heard in all parts of the room. The cylinder is entirely closed, with the exception of a circular opening at the end, near the fork, and in general apppearance resembles a fruit can. When the fork is caused to vibrate thus in connection with a resonator, the sound is instantly extinguished if the aperture be closed, but as it is gradually opened the sound correspondingly gains in intensity, hence it is evidently in the power of the experimentor to regulate the loudness of the tone produced. A tuning-fork, however, soon ceases to vibrate, accordingly it is to be provided with a contrivance to obviate this difficulty. By placing it between the arms of an electro-magnet, having the form of a horse-shoe, it can be caused to vibrate for any period of time, provided the magnetic attraction is intermittent and always exercised at exactly the right moment. This is accomplished by breaking and re-establishing the electric current with the aid of a second tuning fork, which vibrates at exactly the same rate, and the second fork, being also provided with a similar electro-magnet, is able independently to maintain itself in vibration for any length of time, just exactly as is the case with the vibrating attachments so often found on electrical apparatus intended for medical

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purposes. If now with this arrangement, we should attempt to sustain in vibration a third fork, whose rate was *a little* faster or slower than that of its two companions, the result would be a lamentable failure; not so, however, if the rate should happen to be exactly twice, three, four times as great, for then the attractive impulses though fewer in number than might be desirable, still would always be rightly timed. It hence is evident that a series of forks whose rates of vibration are as 1, 2, 3, 4, &c., can be kept simultaneously in vibration for a long period by a contrivance of this kind. And this plan was actually employed by Helmholtz in his celebrated apparatus for the reproduction of the vowel sounds out of pure constituents. Keys were connected with the valves of the cylinders, and pressure on them, opening the resonators, produced the proper notes with the desired strength. Helmholtz's apparatus as made by Mr Kœnig of Paris, so celebrated for his acoustic instruments, consists of eight tuning forks with their resonance cylinders, the fork which establishes and regulates the current, being on a separate stand. These forks give the following notes $Ut_2$, $Ut_3$, $Sol_3$, $Ut_4$, $Mi_4$, $Sol_4$, $Ut_5$, the eigth giving a tone intermediate between the two last. (15.)

When all these tuning forks are caused to vibrate by the electro-magnets, their resonance-cylinders remaining closed, only a low humming sound is heard, but by pressing one or more keys, the corresponding sounds are called forth with any desirable degree of strength.

Thus the German vowel sound U can be imitated either by sounding the $ut_2$ fork alone, or better by adding in small proportion $ut_3$ and $sol_3$. O is obtained, with a weak $ut_2$ and strong $ut_4$; $ut_3$, $sol_3$, and $mi_4$; mingling to a small extent.

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The German A, with $ut_5$ and $mi_4$ strong; $ut_3$, $ut_4$, $sol_4$, being moderate in strength. In the same language the Æ is given by $mi_5$ and $sol_5$ strong, with the notes $ut_4$, $ut_5$, $sol_4$ weaker, and finally the E by the aid of $sol_5$, $si_5$ flat, and $ut_6$, strong, $ut_3$ and $ut_4$ being weaker. (16.)

Of course, inasmuch as only pure musical notes are employed they can reproduce only the musical constituents of the vowel sounds, hence the effect resembles the sound of the vowels as sung rather than pronounced.

When, then, a human being utters merely a vowel sound, its production requires that the cavity and opening of the mouth should have exactly such a size and shape as strengthens the appropriate notes to the proper degree, so that it is indeed no wonder that an infant requires the practice of a year or two before becoming practically familiar with these delicate operations, the real wonder being that children ever learn to talk at all, for the construction of the consonants is far more complex, and although we know for the most part the manipulation necessary for their formation, their composition, so far baffles all attempts at exact analysis. (16.)

Corresponding with these remarkable experiments, Helmholtz also found it possible to imitate with the same apparatus certain varieties of organ pipes, at least, to reproduce the musical constituents of their tones, though, of course the *noise* with which they are often accompanied was absent; he in addition, imitated the nasal tones of the clarionet, by the use of a portion of the forks, while the joint action of the whole set gave the softer tones of the bugle-horn.

This apparatus of Helmholtz, as would be supposed, is somewhat difficult of manipulation, and an attempt has been made by Appun to replace it by a series of reeds provided with resonators. (17.)

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I must here mention the remarkable results, attained in the last century, by Professor V. Kemplen, in Vienna, with his Speaking Machine, which more recently has been greatly perfected by the two Fabers, uncle and nephew. (18.) A few weeks ago the latter kindly exhibited to me this wonderful apparatus, which is capable of uttering, not only syllables, but words and sentences, with great distinctness and a soulless precision, such as we might attribute to the handiwork of a Frankenstein, its laughter being particularly demoniacal—or shall we say idiotic. In it the vocal human organs are directly imitated, and it is remarkable that it is operated on by only fourteen keys or stops, which give the five vowels and the nine consonants, L, R, W, F, S, B, D, G, Sch. The other consonants are produced partly by combinations of the above, and by increasing the strength of the current of air from the bellows. Mr. Faber has, also, after many attempts constructed a singing machine, which, by means of quick changes in the form of the vocal cords can rapidly run through the musical scale.

These illustrations will serve to give some slight idea of the mode in which we speak, and I now pass on to the consideration of that wonderful and mysterious apparatus with which we receive and actually analyze the sounds that are presented to us. We have on the screen a plan of the ear, not a correct drawing, for that would be so complicated as to be of little use. The sound-waves enter the outer ear, and strike on this not tightly-stretched membrane, which we call the drum of the ear, and cause it to vibrate, to bend inward and outward, keeping exact time with the sound vibrations themselves. To this membrane, as you see, are attached three little

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bones, called, respectively, the hammer, the anvil, and the stirrup. The membrane shakes the hammer, the hammer beats the anvil, the anvil vibrates the stirrup, and the stirrup sets in vibration the water in this strangely-shaped cavity, which is colored blue for distinctness. In this cavity, which is not without its unsolved mysteries, the nerves of hearing terminate, and transmit from it the sensation of sound to the brain. A simple arrangement of the kind indicated would transmit to the brain, merely a general sensation of sound, just as the blind on turning their eyes to the sun, have a general sensation of light; but what is the apparatus which enables us to distinguish between different sounds, high and low notes, and notes of different quality? Let us place this question distinctly before ourselves; but before answering it, allow me to repeat for you a beautiful experiment of Tyndall's which has a bearing on its solution. We have here a tall gas flame issuing from a jet, (which was made and given to me years ago by Prof. Mayer of Hoboken,) and I now arrange the pressure on the gas, so that the flame is almost ready to flare or vibrate, of course at a rate of its own selection, and if I send to it sound vibrations of its own chosen kind, it will instantly acknowledge the relationship—it will shorten itself, flare and roar. It pays, for example, no attention to the sound of this two foot organ pipe, but, as you see, instantly responds to the least sound from the bunch of keys. I pronounce to it the vowel sounds; it is evidently deaf to the German U, does not pay much, attention to O, more to E, I, and much more to the sound Ah. As you see, the least hiss, even from this distance, causes it to roar. So we find in a general way, that a stream of gas can be set in vibration by the sound-waves which it has a tendency itself to generate.

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But still more accurately to the point is an experiment with two similar tuning-forks. which I now wish to make. Here are two tuning-forks in all respects alike, mounted on their boxes, and exactly in unison. When I set one of them in action, the feeble sound vibrations, travel through the air, and set the second fork with all its mass of heavy steel also in vibration, simply because it naturally vibrates at exactly the same rate, for owing to this fact, the transmitted vibrations always reach it at the right instant for coöperation, all conflict being avoided. But in this large house the greater number of you would not be able to hear the feeble vibrations of the second fork, and I have contrived this delicately suspended mirror, which, hanging by a hair that is fastened above and below, can be set in motion by the least vibration of the fork in contact with it. The mirror reflects a beam of light on the screen: it is now stationary; but the instant the bow is drawn over its companion, it begins to move, and the motion becomes each moment more violent, till now the spot of light sweeps over the whole screen, and you notice that even at a distance of several feet we have the same result reproduced. By the use of a single silk fibre instead of a hair, the delicacy of the aparatus is so greatly exalted as to render it unfit for a locality like the present. I slightly lower the note of the first fork by loading it with a nickel cent, attaching it with wax, and observe that the second fork with the mirror, now pays no attention to its call; the spot of light remains stationary.

Let us make an application of our experiment. In the ear, in the strangely shaped cavity, we find a multitude of very small elastic rods fastened at one end, just

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like our tuning-fork, and, like it, capable of vibrating only when the particular notes to which they are tuned are struck. When this happens to one of these rods it is set in vibration, and affects the delicate nerve fibril connected with it, and we have the sensation due to a particular rate of vibration, due to a particular note. A drawing of some of these rods enormously magnified is on the screen. But for the full illustration of this matter, I need yet one more experiment, and must ask you to make it for me when you go home this evening. Open a piano, and while pressing with the foot on the right hand pedal, pronounce in a clear loud voice over the strings, for example, the vowel sounds, and you will find that the strings, which are capable of giving the notes of which they are built up, will be set in vibration, and will echo back in a far off, ghostly way, the sound you have just uttered. So in all probability is it in the ear; for we find there, locked up in its bones in the strangely shaped cavity, an instrument with not less than 3,000 strings, tuned, as we believe, to different notes, and connected with different nerve filaments, ready to transmit to the brain the sensations due to different tones. A drawing of a portion of this wonderful contrivance which has been particularly described by the Marchese Corti, is on the screen, and some of the strings can be seen. Its probable action is as follows: When a sound composed of a number of notes, reaches it, the compound tone is analyzed into its constitutents, the corresponding cords vibrate, as in the piano experiment, and by their action on the nerves, reproduce the appropriate sensations. (19.)

The two contrivances I have described are well fitted to make us sensible of sounds which are sufficiently pro-

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longed to allow of the reception of a certain number of vibrations by the sympathetic apparatus in the ear, but in those cases where the vibrations, though powerful, are very few in number, it is probable that the cords and rods would fail to take cognizance of them; that is, they are probably deaf to short, quick sounds, generated by a single blow or impulse, such for example as the electric spark, and yet it is just these sounds which often announce the presence of danger. This case has also been provided for—curiously enough, by introducing into the strangely-shaped cavity, small, rather heavy, solid bodies, which *will not* vibrate readily or easily. In certain parts of the labyrinth, we find particles of calcareous sand imbedded among the delicate nerve filaments, whose office it is to resist their motion, when they tend to vibrate along with the water which fills the cavity, and acting as drags to stretch, and thus stimulate them into activity.

I hold in my hand a long india-rubber string stretched by a weight: if I raise the string slowly, the weight readily follows, and the string is not elongated more than before, but when I attempt suddenly to raise the string the weight resists, the string is greatly lengthened, and it is possible by a quick jerk to cause it, as you see, to separate from the weight. The last form of hearing apparatus is the simplest, the least elaborate of the three, and we find it among the lower animals, where the more complex contrivances are to a greater or less extent absent.

Thus it would seem that nature has provided man with a most elaborate and complicated piece of apparatus, with which it is practicable to perceive and distinguish several thousand simple tones, and the number of their

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possible combinations is, of course, infinite. Think of the delicate care required to keep such an instrument in order, its strings properly weighted and stretched, its rods all in tune, day after day, during the process of growth and waste, to which it, like the rest of the body, is constantly subjected! It gives us no care, we never think of it as in our random way we supply ourselves with such food as we fancy, some of which is sure to be required for its use, and to become eventually incorporated into its tissues—by the aid of an unseen, unfelt hand, whose delicacy of operation surpasses our thought. And with what may seem to us a certain prodigality, we must reflect that the Creator has also bestowed this same beautiful and complicated aparatus, not only on the wildest of savage men, but likewise on many of the higher animals—"brutes that perish"—and with the same fond, all-embracing care, preserves it for them in order during their lives.

The pictures produced on the retina of the eye are evanescent, vanishing with the light which generated them, and the vibrations in the ear which give us the sensations of particular sounds die away with their cause, leaving behind absolutely no record, for that which we retain in the brain, is the recollection of a *sensation*, not of the vibrations which gave it birth. Hence, we must regard with interest and curiosty the beautiful apparatus of Scott and Kœning, with which it is possible to register these vibrations, even when produced by rather complicated sounds; Scott, indeed, hoped at one time, thus to obtain the autographs of sounds uttered by the human voice, though this has been found practicable to some extent *only* with the simple vowel sounds, for which the

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celebrated Donders obtained definite curves, and more recently determined the actual *duration* of one of the vowel-sounds in certain words. (20). We must, perhaps, the less regret our inability to record all sound-vibrations, from the circumstance that the curves thus produced, would by their great complexity defy analysis, by anything short of angellic intelligence.

If you were to tell a thoughtful man who happened to be quite ignorant of the mechanism and action of the voice, that there were living beings who endeavored to express their wishes, thoughts, and feelings, merely by the aid of mechanical vibrations, thus causing the particles of the air to swing like invisible pendulums, backward and forward in certain ways, your listner would be impressed by the poverty of the device, and would too hastily conclude, that only a few of the simplest and rudest ideas could possibly find expression by the aid of a contrivance so clumsy. He would tell you it was conceivable, perhaps, that by appropriate vibrations the idea of joy, or rage, or fear, or possibly of hunger, might be imperfectly expressed, with a few others of like character, but that to expect more would be visionary. He would urge that all vibrations were necessarily so similar in general character, that it would be impossible to communicate to them the stamp of thought or feeling. And yet how wonderfully each one of us employs just such vibrations, and with a skill which seems truly superhuman impresses upon and commits to them an infinite variety of thoughts, feelings, and ideas which at times we pour forth in torrents that seem inexhaustible; the vastness of the result attained, the poverty of the means are utterly overwhelming !

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Think, also, for a moment of that gift by which we read the stories written on the invisible waves of the air, how we instantly interpret and disentangle their complexities, as they roll in towards us, thousands in a second, with the velocity of rifle-bullets. The power to hear and speak are gifts, which, from purely physical and mathematical standpoints, are absolutely magnificent! And we the possessors of such powers? Is it conceivable that they have been bestowed on us only to be used as at present? Do they not point to a future for our race when they will be employed in a manner which better accords with their inexpressible richness and grandeur?

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# Notes and References.

(1) The constitution of waves of water was carefully examined by the brothers Weber, and their remarkable investigation while adding greatly to our knowledge of the subject, at the same time has shown that here, as elsewhere in nature, complexity is the rule, simplicity only apparent. Troughs provided with glass sides, and about six feet in length were employed, the wave being generated at one end by means of a tube containing a column of water of a certain height. The sudden fall of this liquid gave the required impulse with accuracy; the wave was then observed through the glass sides by the naked eye or with a low-power microscope, which was provided with a simple micrometric attachment. In order to facilitate the study of layers below the surface, the water held in supension small fragments of amber, which made visible the motions of the liquid.

In this manner they found that the particles of water when traversed by waves do not merely rise and fall, but at the same time have a motion backwards and forwards, which would assign these waves a position intermediate between those of sound and light. In point of fact they described ellipses, when the waves were perfectly regular in form; when however this regularity was absent, other curves not returning into themselves were generated. In these experiments the mountain was always in advance, unless the wave was generated not by the fall of a column of water, but by effecting with a little pump its sudden *rise*; in this latter case the valley formed the advancing front of the wave. Finally it was ascertained that the surface-waves affected the particles of water under them, to a depth of not less than 350 times the height of a wave. Many of the phenomena are beautifully illustrated by an ingenious apparatus which a few years ago was contrived by Prof. Lyman of New Haven. American Journal of Science and Arts, Vol. xlv., p. 384.

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